Chapter 21 | Coulomb’s Law

\[ F = \frac{Gm_1m_2}{r^2} \]

\[ = \frac{(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2)(1.67 \times 10^{-27} \text{ kg})^2}{(4.0 \times 10^{-15} \text{ m})^2} \]

\[ = 1.2 \times 10^{-35} \text{ N.} \]

(Answer)

**Weak versus strong:** This result tells us that the (attractive) gravitational force is far too weak to counter the repulsive electrostatic forces between protons in a nucleus. Instead, the protons are bound together by an enormous force called (aptly) the strong nuclear force—a force that acts between protons (and neutrons) when they are close together, as in a nucleus.

Although the gravitational force is many times weaker than the electrostatic force, it is more important in large-scale situations because it is always attractive. This means that it can collect many small bodies into huge bodies with huge masses, such as planets and stars, that then exert large gravitational forces. The electrostatic force, on the other hand, is repulsive for charges of the same sign, so it is unable to collect either positive charge or negative charge into large concentrations that would then exert large electrostatic forces.

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**21-6 | Charge Is Conserved**

If you rub a glass rod with silk, a positive charge appears on the rod. Measurement shows that a negative charge of equal magnitude appears on the silk. This suggests that rubbing does not create charge but only transfers it from one body to another, upsetting the electrical neutrality of each body during the process. This hypothesis of **conservation of charge**, first put forward by Benjamin Franklin, has stood up under close examination, both for large-scale charged bodies and for atoms, nuclei, and elementary particles. No exceptions have ever been found. Thus, we add electric charge to our list of quantities—including energy and both linear and angular momentum—that obey a conservation law.

Important examples of the conservation of charge occur in the radioactive decay of nuclei, in which a nucleus transforms into (becomes) a different type of nucleus. For example, a uranium-238 nucleus \(^{238}\text{U}\) transforms into a thorium-234 nucleus \(^{234}\text{Th}\) by emitting an alpha particle. Because that particle has the same makeup as a helium-4 nucleus, it has the symbol \(^4\text{He}\). The number used in the name of a nucleus and as a superscript in the symbol for the nucleus is called the **mass number** and is the total number of the protons and neutrons in the nucleus. For example, the total number in \(^{238}\text{U}\) is 238. The number of protons in a nucleus is the **atomic number** \(Z\), which is listed for all the elements in Appendix F. From that list we find that in the decay

\[ ^{238}\text{U} \rightarrow ^{234}\text{Th} + ^4\text{He}, \tag{21-13} \]

the *parent* nucleus \(^{238}\text{U}\) contains 92 protons (a charge of +92e), the *daughter* nucleus \(^{234}\text{Th}\) contains 90 protons (a charge of +90e), and the emitted alpha particle \(^4\text{He}\) contains 2 protons (a charge of +2e). We see that the total charge is +92e before and after the decay; thus, charge is conserved. (The total number of protons and neutrons is also conserved: 238 before the decay and 234 + 4 = 238 after the decay.)

Another example of charge conservation occurs when an electron \(e^-\) (whose charge is \(-e\)) and its antiparticle, the positron \(e^+\) (whose charge is \(+e\)), undergo an **annihilation process** in which they transform into two gamma rays (high-energy light):

\[ e^- + e^+ \rightarrow \gamma + \gamma \quad \text{(annihilation).} \tag{21-14} \]

In applying the conservation-of-charge principle, we must add the charges algebraically, with due regard for their signs. In the annihilation process of Eq. 21-14 then, the net charge of the system is zero both before and after the event. Charge is conserved.

In **pair production**, the converse of annihilation, charge is also conserved. In this process a gamma ray transforms into an electron and a positron:

\[ \gamma \rightarrow e^- + e^+ \quad \text{(pair production).} \tag{21-15} \]

Figure 21-12 shows such a pair-production event that occurred in a bubble cham-
ber. A gamma ray entered the chamber from the bottom and at one point transformed into an electron and a positron. Because those new particles were charged and moving, each left a trail of tiny bubbles. (The trails were curved because a magnetic field had been set up in the chamber.) The gamma ray, being electrically neutral, left no trail. Still, you can tell exactly where it underwent pair production—at the tip of the curved V, which is where the trails of the electron and positron begin.

**REVIEW & SUMMARY**

**Electric Charge**  The strength of a particle's electrical interaction with objects around it depends on its electric charge, which can be either positive or negative. Charges with the same sign repel each other, and charges with opposite signs attract each other. An object with equal amounts of the two kinds of charge is electrically neutral, whereas one with an imbalance is electrically charged.

**Conductors** are materials in which a significant number of charged particles (electrons in metals) are free to move. The charged particles in **nonconductors**, or **insulators**, are not free to move.

**The Coulomb and Ampere**  The SI unit of charge is the **coulomb** (C). It is defined in terms of the unit of current, the ampere (A), as the charge passing a particular point in 1 second when there is a current of 1 ampere at that point:

\[ 1 \text{ C} = (1 \text{ A})(1 \text{ s}). \]

This is based on the relation between current \(i\) and the rate \(dq/dt\) at which charge passes a point:

\[ i = \frac{dq}{dt} \quad \text{(electric current)}. \quad (21-3) \]

**Coulomb's Law**  **Coulomb's law** describes the electrostatic force between small (point) electric charges \(q_1\) and \(q_2\) at rest (or nearly at rest) and separated by a distance \(r\):

\[ F = \frac{1}{4\pi\varepsilon_0} \frac{|q_1| |q_2|}{r^2} \quad \text{(Coulomb's law)}. \quad (21-4) \]

Here \(\varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2\) is the **permittivity constant**, and \(1/4\pi\varepsilon_0 = k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2\).

The force of attraction or repulsion between point charges at rest acts along the line joining the two charges. If more than two charges are present, Eq. 21-4 holds for each pair of charges. The net force on each charge is then found, using the superposition principle, as the vector sum of the forces exerted on the charge by all the others.

The two shell theorems for electrostatics are

A shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell's charge were concentrated at its center.

If a charged particle is located inside a shell of uniform charge, there is no net electrostatic force on the particle from the shell.

**The Elementary Charge**  Electric charge is **quantized**: any charge can be written as \(ne\), where \(n\) is a positive or negative integer and \(e\) is a constant of nature called the **elementary charge** (≈ 1.602 × 10^{-19} \text{ C}). Electric charge is **conserved**: the net charge of any isolated system cannot change.

**QUESTIONS**

1. Figure 21-13 shows four situations in which charged particles are fixed in place on an axis. In which situations is there a point to the left of the particles where an electron will be in equilibrium?

   ![Figure 21-13](image)

   Question 1.

2. Figure 21-14 shows two charged particles on an axis. The charges are free to move. However, a third charged particle can be placed at a certain point such that all three particles are then in equilibrium. (a) Is that point to the left of the first two particles, to their right, or between them? (b) Should the third particle be positively or negatively charged? (c) Is the equilibrium stable or unstable?

   ![Figure 21-14](image)

   Question 2.

3. Figure 21-15 shows four situations in which five charged particles are evenly spaced along an axis. The charge values are indicated except for the central particle, which has the same charge in all four situations. Rank the situations according to the magnitude of the net electrostatic force on the central particle, greatest first.

   ![Figure 21-15](image)

   Question 3.

4. Figure 21-16 shows three pairs of identical spheres that are to be touched together and then separated. The initial charges on them are indicated. Rank the pairs according to (a) the mag-
5 Figure 21-17 shows three situations involving a charged particle and a uniformly charged spherical shell. The charges are given, and the radii of the shells are indicated. Rank the situations according to the magnitude of the force on the particle due to the presence of the shell, greatest first.

![Diagram of charged particles and shell](image)

**FIG. 21-17** Question 5.

6 In Fig. 21-18, a central particle of charge \(-2q\) is surrounded by a square array of charged particles, separated by either distance \(d\) or \(d/2\) along the perimeter of the square. What are the magnitude and direction of the net electrostatic force on the central particle due to the other particles? (Hint: Consideration of symmetry can greatly reduce the amount of work required here.)

![Diagram of charged particles](image)

**FIG. 21-18** Question 6.

7 In Fig. 21-19, a central particle of charge \(-q\) is surrounded by two circular rings of charged particles. What are the magnitude and direction of the net electrostatic force on the central particle due to the other particles? (Hint: Consideration of symmetry can greatly reduce the amount of work required here.)

![Diagram of charged particles](image)

**FIG. 21-19** Question 7.

8 A positively charged ball is brought close to an electrically neutral isolated conductor. The conductor is then grounded while the ball is kept close. Is the conductor charged positively, charged negatively, or neutral if (a) the ball is first taken away and then the ground connection is removed and (b) the ground connection is first removed and then the ball is taken away?

9 Figure 21-20 shows four situations in which particles of charge \(+q\) or \(-q\) are fixed in place. In each situation, the particles on the \(x\) axis are equidistant from the \(y\) axis. First, consider the middle particle in situation 1; the middle particle experiences an electrostatic force from each of the other two particles. (a) Are the magnitudes \(F\) of those forces the same or different? (b) Is the magnitude of the net force on the middle particle equal to, greater than, or less than \(2F\)? (c) Do the \(x\) components of the two forces add or cancel? (d) Do their \(y\) components add or cancel? (e) Is the direction of the net force on the middle particle that of the canceling components or the adding components? (f) What is the direction of that net force? Now consider the remaining situations: What is the direction of the net force on the middle particle in (g) situation 2, (h) situation 3, and (i) situation 4? (In each situation, consider the symmetry of the charge distribution and determine the canceling components and the adding components.)

![Diagram of charged particles](image)

**FIG. 21-20** Question 9.

10 Figure 21-21 shows four arrangements of charged particles. Rank the arrangements according to the magnitude of the net electrostatic force on the particle with charge \(+Q\), greatest first.

![Diagram of charged particles](image)

**FIG. 21-21** Question 10.
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1. What must be the distance between point charge \( q_1 = 26.0 \mu C \) and point charge \( q_2 = -47.0 \mu C \) for the electrostatic force between them to have a magnitude of 5.70 N? 

2. Two equally charged particles are held 3.2 \( \times 10^{-3} \) m apart and then released from rest. The initial acceleration of the first particle is observed to be 7.0 m/s\(^2\) and that of the second to be 9.0 m/s\(^2\). If the mass of the first particle is 6.3 \( \times 10^{-7} \) kg, what are \( (a) \) the mass of the second particle and \( (b) \) the magnitude of the charge of each particle? 

3. A particle of charge \( +3.00 \times 10^{-6} \) C is 12.0 cm distant from a second particle of charge \( -1.50 \times 10^{-6} \) C. Calculate the magnitude of the electrostatic force between the particles. 

4. Identical isolated conducting spheres 1 and 2 have equal charges and are separated by a distance that is large compared with their diameters (Fig. 21-22a). The electrostatic force acting on sphere 2 due to sphere 1 is \( F \). Suppose now that a third identical sphere 3, having an insulating handle and initially neutral, is touched first to sphere 1 (Fig. 21-22b), then to sphere 2 (Fig. 21-22c), and finally removed (Fig. 21-22d). The electrostatic force that now acts on sphere 2 has magnitude \( F' \). What is the ratio \( F'/F \)? 

5. Of the charge \( Q \) initially on a tiny sphere, a portion \( q \) is to be transferred to a second, nearby sphere. Both spheres can be treated as particles. For what value of \( q/Q \) will the electrostatic force between the two spheres be maximized? 

6. In the return stroke of a typical lightning bolt, a current of \( 2.5 \times 10^4 \) A exists for 20 \( \mu \)s. How much charge is transferred in this event? 

7. Two identical conducting spheres, fixed in place, attract each other with an electrostatic force of 0.108 N when their center-to-center separation is 50.0 cm. The spheres are then connected by a thin conducting wire. When the wire is removed, the spheres repel each other with an electrostatic force of 0.0360 N. Of the initial charges on the spheres, with a positive net charge, what was \( (a) \) the negative charge on one of them and \( (b) \) the positive charge on the other? 

8. In Fig. 21-23, four particles form a square. The charges are \( q_1 = q_2 = Q \) and \( q_3 = q_4 = q \). \( (a) \) What is \( Q/q \) if the net electrostatic force on particles 1 and 4 is zero? \( (b) \) Is there any value of \( q \) that makes the net electrostatic force on each of the four particles zero? Explain. 

9. In Fig. 21-23, the particles have charges \( q_1 = -q_2 = 100 \) nC and \( q_3 = -q_4 = 200 \) nC, and distance \( a = 5.0 \) cm. What are the \( (a) x \) and \( (b) y \) components of the net electrostatic force on particle 3? 

10. Three particles are fixed on an \( x \) axis. Particle 1 of charge \( q_1 \) is at \( x = -a \), and particle 2 of charge \( q_2 \) is at \( x = +a \). If their net electrostatic force on particle 3 of charge \( +Q \) is to be zero, what must be the ratio \( q_1/q_2 \) when particle 3 is at \( (a) x = +0.500a \) and \( (b) x = +1.50a \)? 

11. In Fig. 21-24, three charged particles lie on an \( x \) axis. Particles 1 and 2 are fixed in place. Particle 3 is free to move, but the net electrostatic force on it from particles 1 and 2 happens to be zero. If \( L_{23} = L_{12} \), what is the ratio \( q_1/q_2 \)? 

12. Figure 21-25 shows four identical conducting spheres that are actually well separated from one another. Sphere \( W \) (with an initial charge of zero) is touched to sphere \( A \) and then they are separated. Next, sphere \( W \) is touched to sphere \( B \) (with an initial charge of \( -32e \)) and then they are separated. Finally, sphere \( W \) is touched to sphere \( C \) (with an initial charge of \( +48e \)), and then they are separated. The final charge on sphere \( W \) is \( +18e \). What was the initial charge on sphere \( A \)? 

13. In Fig. 21-26a, particles 1 and 2 have charge \( 20.0 \mu C \) each and are held at separation distance \( d = 1.50 \) m. \( (a) \) What is the magnitude of the electrostatic force on particle 1 due to particle 2? In Fig. 21-26b, particle 3 of charge \( 20.0 \mu C \) is positioned so as to complete an equilateral triangle. \( (b) \) What is the magnitude of the net electrostatic force on particle 1 due to particles 2 and 3?
**••14** In Fig. 21-27a, particle 1 (of charge $q_1$) and particle 2 (of charge $q_2$) are fixed in place on an $x$ axis, 8.00 cm apart. Particle 3 (of charge $q_3 = +8.00 \times 10^{-19}$ C) is to be placed on the line between particles 1 and 2 so that they produce a net electrostatic force $F_{\text{net}}$ on it. Figure 21-27b gives the $x$ component of that force versus the coordinate $x$ at which particle 3 is placed. The scale of the $x$ axis is set by $x_s = 8.0$ cm. What are (a) the sign of charge $q_1$ and (b) the ratio $q_2/q_1$?

![FIG. 21-27](image)

**Problem 14.**

**••15** In Fig. 21-28, particle 1 of charge $+1.0 \mu$C and particle 2 of charge $-3.0 \mu$C are held at separation $L = 10.0$ cm on an $x$ axis. If particle 3 of unknown charge $q_3$ is to be located such that the net electrostatic force on it from particles 1 and 2 is zero, what must be the (a) $x$ and (b) $y$ coordinates of particle 3?

![FIG. 21-28](image)

**Problems 15, 19, 32, 64, and 69.**

**••16** In Fig. 21-29, three positively charged particles are fixed on an $x$ axis. Particles $B$ and $C$ are so close to each other that they can be considered to be at the same distance from particle $A$. The net force on particle $A$ due to particles $B$ and $C$ is $2.014 \times 10^{-23}$ N in the negative direction of the $x$ axis. In Fig. 21-29b, particle $B$ has been moved to the opposite side of $A$ but is still at the same distance from it. The net force on $A$ is now $2.877 \times 10^{-24}$ N in the negative direction of the $x$ axis. What is the ratio $q_C/q_B$?

![FIG. 21-29](image)

**Problem 16.**

**••17** The charges and coordinates of two charged particles held fixed in an $xy$ plane are $q_1 = +3.0 \mu$C, $x_1 = 3.5$ cm, $y_1 = 0.50$ cm, and $q_2 = -4.0 \mu$C, $x_2 = -2.0$ cm, $y_2 = 1.5$ cm. Find the (a) magnitude and (b) direction of the electrostatic force on particle 2 due to particle 1. At what (c) $x$ and (d) $y$ coordinates should a third particle of charge $q_3 = +4.0 \mu$C be placed such that the net electrostatic force on particle 2 due to particles 1 and 3 is zero?

**••18** Two particles are fixed on an $x$ axis. Particle 1 of charge $40 \mu$C is located at $x = -2.0$ cm; particle 2 of charge $Q$ is located at $x = 3.0$ cm. Particle 3 of charge magnitude $20 \mu$C is released from rest on the $y$ axis at $y = 2.0$ cm. What is the value of $Q$ if the initial acceleration of particle 3 is in the positive direction of (a) the $x$ axis and (b) the $y$ axis?

**••19** In Fig. 21-28, particle 1 of charge $+q$ and particle 2 of charge $+4.00q$ are held at separation $L = 9.00$ cm on an $x$ axis. If particle 3 of charge $q_3$ is to be located such that the three particles remain in place when released, must be the (a) $x$ and (b) $y$ coordinates of particle 3, and (c) the ratio $q_3/q$?  

**••20** Figure 21-30 shows an arrangement of four charged particles, with angle $\theta = 30.0^\circ$ and distance $d = 2.00$ cm. Particle 2 has charge $q_2 = +8.00 \times 10^{-19}$ C; particles 3 and 4 have charges $q_3 = q_4 = -1.60 \times 10^{-19}$ C. (a) What is the distance $D$ between the origin and particle 2 if the net electrostatic force on particle 1 due to the other particles is zero? (b) If particles 3 and 4 were moved closer to the $x$ axis but maintained their symmetry about that axis, would the required value of $D$ be greater than, less than, or the same as in part (a)?

![FIG. 21-30](image)

**Problem 20.**

**••21** In Fig. 21-31, particles 1 and 2 of charge $q_1 = q_2 = +320 \times 10^{-19}$ C are on a $y$ axis at distance $d = 17.0$ cm from the origin. Particle 3 of charge $q_3 = +640 \times 10^{-19}$ C is moved gradually along the $x$ axis from $x = 0$ to $x = +5.0$ m. At what values of $x$ will the magnitude of the electrostatic force on the third particle from the other two particles be (a) minimum and (b) maximum? What are the (c) minimum and (d) maximum magnitudes?

![FIG. 21-31](image)

**Problem 21.**

**••22** Figure 21-32a shows an arrangement of three charged particles separated by distance $d$. Particles $A$ and $C$ are fixed on the $x$ axis, but particle $B$ can be moved along a circle centered on particle $A$. During the movement, a radial line between $A$ and $B$ makes an angle $\theta$ relative to the positive direction of the $x$ axis (Fig. 21-32b). The curves in Fig. 21-32c give, for two situations, the magnitude $F_{\text{net}}$ of the net electrostatic force on particle $A$ due to the other particles. That net force is given as a function of angle $\theta$ and as a multiple of a basic amount $F_0$. For example on curve 1, at $\theta = 180^\circ$, we see that $F_{\text{net}} = 2F_0$. (a) For the situation corresponding to curve 1, what is the ratio of the charge of particle $C$ to that of particle $B$ (including sign)? (b) For the situation corresponding to curve 2, what is that ratio?

![FIG. 21-32](image)

**Problem 22.**

**••23** A nonconducting spherical shell, with an inner radius of 4.0 cm and an outer radius of 6.0 cm, has charge spread nonuniformly through its volume between its inner and outer surfaces. The volume charge density $\rho$ is the charge per unit volume, with the unit coulomb per cubic meter. For this shell $\rho = b/r$, where $r$ is the distance in meters from the center of the shell and $b = 3.0 \mu$C/m². What is the net charge in the shell?

**sec. 21-5 Charge Is Quantized**

**••24** What is the magnitude of the electrostatic force between
1. The charge on a singly charged sodium ion (Na\(^+\), of charge +e) and an anion, a singly charged chloride ion (Cl\(^-\), of charge -e) in a salt is 2.82 × 10\(^{-10}\) m. The magnitude of the electric force between two identical ions that are separated by a distance of 5.0 × 10\(^{-10}\) m is 3.7 × 10\(^{-9}\) N. (a) What is the charge of each ion? (b) How many electrons are "missing" from each ion (thus giving the ion its charge imbalance)? 

A current of 0.300 A through your chest can send your heart into fibrillation, ruining the normal rhythm of heartbeat disrupting the flow of blood (and thus oxygen) to your cells. If that current persists for 2.00 min, how many conductive electrons pass through your chest? 

How many electrons would have to be removed from a 1000 C to leave it with a charge of +1.0 × 10\(^{-7}\) C? 

Two tiny, spherical water drops, with identical charges -1.00 × 10\(^{-10}\) C, have a center-to-center separation of 1.00 cm. (a) What is the magnitude of the electrostatic force acting on them? (b) How many excess electrons are on each drop, giving it its charge imbalance? 

Earth’s atmosphere is constantly bombarded by cosmic rays that originate somewhere in space. If the protons pass through the atmosphere, each square meter of earth’s surface would intercept protons at the average rate of 100 protons per second. What would be the electric current intercepted by the total surface area of the planet? 

A figure shows charged particles 1 and 2 that are fixed in place on an x axis. Particle 1 has a charge with a magnitude |q_1| = 8.00e. Particle 3 of charge q_3 = +8.00e is initially on the x axis near particle 2. Then particle 3 is gradually moved in the positive direction of the x axis. As a result, the magnitude of the net electrostatic force \(F_{\text{net}}\) on particle 2 due to particles 1 and 3 changes. Figure 21-33b gives the x component of that net force as a function of the position x of particle 3. The scale of the x axis is set by the origin of particle 2. The plot has an asymptote of \(F_{\text{net}} = 1.5 \times 10^{-25}\) N as x → ∞. As a multiple of e and including the sign, what is the charge q_3 of particle 2? 

**Problem 30.**

**Problem 31.** Calculate the number of coulombs of positive charge in 250 cm\(^3\) of (neutral) water. (Hint: A hydrogen atom contains one proton; an oxygen atom contains eight protons.) 

**Problem 32.** In Fig. 21-28, particles 1 and 2 are fixed in place on an x axis, at a separation of L = 8.00 cm. Their charges are q_1 = +e and q_2 = -27e. Particle 3 with charge q_3 = +4e is to be placed on the line between particles 1 and 2, so that they produce a net electrostatic force \(F_{\text{net}}\) on it. (a) At what coordinate should particle 3 be placed to minimize the magnitude of that force? (b) What is that minimum magnitude? 

**Problem 33.** In Fig. 21-34, particles 2 and 4, of charge -e, are fixed in place on a y axis, at \(y_2 = -10.0\) cm and \(y_4 = 5.00\) cm. Particles 1 and 3, of charge +e, can be moved along the x axis. Particle 5, of charge +e, is fixed at the origin. Initially particle 1 is at \(x_1 = -10.0\) cm and particle 3 is at \(x_3 = 10.0\) cm. (a) To what x value must particle 1 be moved to rotate the direction of the net electric force \(F_{\text{net}}\) on particle 5 by 30° counterclockwise? (b) With particle 1 fixed at its new position, to what x value must you move particle 3 to rotate \(F_{\text{net}}\) back to its original direction? 

**Problem 34.** Figure 21-35 shows electrons 1 and 2 and 3 and 4 on an x axis and charged ions 3 and 4 of identical charge -q at identical angles \(\theta\). Electron 2 is free to move; the other three particles are fixed in place at horizontal distances R from electron 2 and are intended to hold electron 2 in place. For physically possible values of q ≤ 5e, what are the (a) smallest, (b) second smallest, and (c) third smallest values of \(\theta\) for which electron 2 is held in place? 

**Problem 35.** In crystals of the salt cesium chloride, cesium ions Cs\(^+\) form the eight corners of a cube and a chlorine ion Cl\(^-\) is at the cube’s center (Fig. 21-36). The edge length of the cube is 0.40 nm. The Cs\(^+\) ions are each deficient by one electron (and thus each has a charge of +e), and the Cl\(^-\) ion has one excess electron (and thus has a charge of -e). (a) What is the magnitude of the net electrostatic force exerted on the Cl\(^-\) ion by the eight Cs\(^+\) ions at the corners of the cube? (b) If one of the Cs\(^+\) ions is missing, the crystal is said to have a defect; what is the magnitude of the net electrostatic force exerted on the Cl\(^-\) ion by the seven remaining Cs\(^+\) ions? 

**Problem 36.** Electrons and positrons are produced by the nuclear transformations of protons and neutrons known as beta decay. (a) If a proton transforms into a neutron, is an electron or a positron produced? (b) If a neutron transforms into a proton, is an electron or a positron produced? 

**Problem 37.** Identify X in the following nuclear reactions: (a) \(^1\)H + \(^9\)Be → X + n; (b) \(^12\)C + \(^1\)H → X; (c) \(^15\)N + \(^1\)H → \(^4\)He + X. Appendix F will help. 

**Additional Problems**

In Fig. 21-37, four particles are fixed along an x axis, separate...
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-rated by distances \( d = 2.00 \text{ cm} \). The charges are \( q_1 = +2e \), \( q_2 = -e \), \( q_3 = +e \), and \( q_4 = +4e \), with \( e = 1.60 \times 10^{-19} \text{ C} \). In unit-vector notation, what is the net electrostatic force on (a) particle 1 and (b) particle 2 due to the other particles?

39 In Fig. 21-38, particle 1 of charge \( +4e \) is above a floor by distance \( d_1 = 2.00 \text{ mm} \) and particle 2 of charge \( +6e \) is on the floor, at distance \( d_2 = 6.00 \text{ mm} \) horizontally from particle 1. What is the \( x \)-component of the electrostatic force on particle 2 due to particle 1?

40 A particle of charge \( Q \) is fixed at the origin of an \( xy \) coordinate system. At \( t = 0 \) a particle \( (m = 0.800 \text{ g}, q = 4.00 \mu \text{ C}) \) is located on the \( x \)-axis at \( x = 20.0 \text{ cm} \), moving with a speed of \( 50.0 \text{ m/s} \) in the positive \( y \)-direction. For what value of \( Q \) will the moving particle execute circular motion? (Neglect the gravitational force on the particle.)

41 A charged nonconducting rod, with a length of \( 2.00 \text{ m} \) and a cross-sectional area of \( 4.00 \text{ cm}^2 \), lies along the positive side of an \( x \)-axis with one end at the origin. The volume charge density \( \rho \) is charge per unit volume in coulombs per cubic meter. How many excess electrons are on the rod if \( \rho \) is (a) uniform, with a value of \(-4.00 \mu \text{ C/m}^3 \), and (b) nonuniform, with a value given by \( \rho = bx^2 \), where \( b = -2.00 \mu \text{ C/m}^3 \)?

42 A charge of \( 6.0 \mu \text{ C} \) is to be split into two parts that are then separated by \( 3.0 \text{ mm} \). What is the maximum possible magnitude of the electrostatic force between those two parts?

43 How many megacoulombs of positive charge are in \( 1.00 \text{ mol} \) of neutral molecular-hydrogen gas \((\text{H}_2)\)?

44 Figure 21-39 shows a long, nonconducting, massless rod of length \( L \), pivoted at its center and balanced with a block of weight \( W \) at a distance \( x \) from the left end. At the left and right ends of the rod are attached small conducting spheres with positive charges \( q \) and \( 2q \), respectively. A distance \( h \) directly beneath each of these spheres is a fixed sphere with positive charge \( Q \). (a) Find the distance \( x \) when the rod is horizontal and balanced. (b) What value should \( h \) have so that the rod exerts no vertical force on the bearing when the rod is horizontal and balanced?

45 A neutron consists of one “up” quark of charge \( +2e/3 \) and two “down” quarks each having charge \(-e/3 \). If we assume that the down quarks are \( 2.6 \times 10^{-15} \text{ m} \) apart inside the neutron, what is the magnitude of the electrostatic force between them?

46 In Fig. 21-40, three identical conducting spheres form an equilateral triangle of side length \( d = 20.0 \text{ cm} \). The sphere radii are much smaller than \( d \), and the sphere charges are \( q_A = -2.00 \text{ nC} \), \( q_B = -4.00 \text{ nC} \), and \( q_C = +8.00 \text{ nC} \). (a) What is the magnitude of the electrostatic force between spheres \( A \) and \( C \)? The following steps are then taken: \( A \) and \( B \) are connected by a thin wire and then disconnected; \( B \) is grounded by the wire, and the wire is then removed; \( B \) and \( C \) are connected by the wire and then disconnected. What are the magnitudes of the electrostatic force (b) between spheres \( A \) and \( C \) and (c) between spheres \( B \) and \( C \)?

47 What would be the magnitude of the electrostatic force between two \( 1.00 \text{ C} \) point charges separated by a distance of (a) \( 1.00 \text{ m} \) and (b) \( 1.00 \text{ km} \) if such point charges existed (they do not) and this configuration could be set up?

48 In Fig. 21-41, three identical conducting spheres initially have the following charges: sphere \( A \), \( 4Q \); sphere \( B \), \(-6Q \); and sphere \( C \), \( 0 \). Spheres \( A \) and \( B \) are fixed in place, with a center-to-center separation that is much larger than the spheres. Two experiments are conducted. In experiment 1, sphere \( C \) is touched to sphere \( A \) and then (separately) to sphere \( B \), and then it is removed. In experiment 2, starting with the same initial states, the procedure is reversed: Sphere \( C \) is touched to sphere \( B \) and then (separately) to sphere \( A \), and then it is removed. What is the ratio of the electrostatic force between \( A \) and \( B \) at the end of experiment 2 to that at the end of experiment 1?

49 We know that the negative charge on the electron and the positive charge on the proton are equal. Suppose, however, that these magnitudes differ from each other by 0.00010%. With what force would two copper coins, placed 1.0 m apart, repel each other? Assume that each coin contains \( 3 \times 10^{22} \) copper atoms. (Hint: A neutral copper atom contains 29 protons and 29 electrons.) What do you conclude?

50 How far apart must two protons be if the magnitude of the electrostatic force acting on either one due to the other is equal to the magnitude of the gravitational force on a proton at Earth’s surface?

51 Of the charge \( Q \) on a tiny sphere, a fraction \( \alpha \) is to be transferred to a second, nearby sphere. The spheres can be treated as particles. (a) What value of \( \alpha \) maximizes the magnitude \( F \) of the electrostatic force between the two spheres? What are the (b) smaller and (c) larger values of \( \alpha \) that put \( F \) at half the maximum magnitude?

52 If a cat repeatedly rubs against your cotton slacks on a dry day, the charge transfer between the cat hair and the cotton can leave you with an excess charge of \(-2.00 \mu \text{ C} \). (a) How many electrons are transferred between you and the cat? You will gradually discharge via the floor, but if instead of waiting, you immediately reach toward a faucet, a painful spark can suddenly appear as your fingers near the faucet. (b) In that spark, do electrons flow from you to the faucet or vice versa? (c) Just before the spark appears, do you induce positive or negative charge in the faucet? (d) If, instead, the cat reaches a paw toward the faucet, which way do electrons flow?
flow in the resulting spark? (c) If you stroked a cat with a bare hand on a dry day, you should take care not to bring your fingers near the cat’s nose or you will hurt it with a spark. Considering that cat hair is an insulator, explain how the spark can appear.

53 (a) What equal positive charges would have to be placed on Earth and on the Moon to neutralize their gravitational attraction? (b) Why don’t you need to know the lunar distance to solve this problem? (c) How many kilograms of hydrogen ions (that is, protons) would be needed to provide the positive charge calculated in (a)?

54 In Fig. 21-42, two tiny conducting balls of identical mass $m$ and identical charge $q$ hang from nonconducting threads of length $L$. Assume that $\theta$ is so small that tan $\theta$ can be replaced by its approximate equal, sin $\theta$. (a) Show that

$$ x = \left(\frac{q^2L^2}{2\pi\varepsilon_0 mg}\right)^{1/3} $$

gives the equilibrium separation $x$ of the balls. (b) If $L = 120$ cm, $m = 10$ g, and $x = 5.0$ cm, what is $iq$?

55 (a) Explain what happens to the balls of Problem 54 if one of them is discharged (loses its charge $q$ to, say, the ground). (b) Find the new equilibrium separation $x$, using the given values of $L$ and $m$ and the computed value of $iq$.

56 In Fig. 21-24, particles 1 and 2 are fixed in place, but particle 3 is free to move. If the net electrostatic force on particle 3 due to particles 1 and 2 is zero and $L_{12} = 2.00L_{12}$, what is the ratio $q_1/q_2$?

57 What is the total charge in coulombs of 75.0 kg of electrons?

58 In Fig. 21-43, six charged particles surround particle 7 at radial distances of either $d = 1.0$ cm or $2d$, as drawn. The charges are $q_1 = +2e, q_2 = +4e, q_3 = +e, q_4 = +4e, q_5 = +2e, q_6 = +8e, q_7 = +6e$, with $e = 1.60 \times 10^{-19}$ C. What is the magnitude of the net electrostatic force on particle 7?

59 Three charged particles form a triangle: particle 1 with charge $Q_1 = 80.0$ nC is at $xy$ coordinates $(0, 3.00)$ mm, particle 2 with charge $Q_2$ is at $(0, -3.00)$ mm, and particle 3 with charge $Q_3 = 18.0$ nC is at $(4.00$ mm, 0). In unit-vector notation, what is the electrostatic force on particle 3 due to the other two particles if $Q_2$ is equal to (a) 80.0 nC and (b) $-80.0$ nC?

60 In Fig. 21-44, what are the (a) magnitude and (b) direction of the net electrostatic force on particle 4 due to the other three particles? All four particles are fixed in the $xy$ plane, and $q_1 = -3.20 \times 10^{-19}$ C, $q_2 = +3.20 \times 10^{-19}$ C, $q_3 = +6.40 \times 10^{-19}$ C, $q_4 = +3.20 \times 10^{-19}$ C, $\theta_1 = 35.0^\circ$, $d_3 = 3.00$ cm, and $d_4 = d_2 = 2.00$ cm. 55M

61 Two point charges of 30 nC and $-40$ nC are held fixed on an $x$ axis, at the origin and at $x = 72$ cm, respectively. A particle with a charge of 42 $\mu$C is released from rest at $x = 28$ cm. If the initial acceleration of the particle has a magnitude of 100 km/s$^2$, what is the particle’s mass?

62 In Fig. 21-23, four particles form a square. The charges are $q_1 = +Q, q_2 = q_3 = q$, and $q_4 = -2.00Q$. What is $q/Q$ if the net electrostatic force on particle 1 is zero?

63 Point charges of $+6.0 \mu$C and $-4.0 \mu$C are placed on an $x$ axis, at $x = 8.0$ m and $x = 16$ m, respectively. What charge must be placed at $x = 24$ m so that any charge placed at the origin would experience no electrostatic force?

64 In Fig. 21-28, particle 1 of charge $-80.0 \mu$C and particle 2 of charge $+40.0 \mu$C are held at separation $L = 20.0$ cm on an $x$ axis. In unit-vector notation, what is the net electrostatic force on particle 3, of charge $q_3 = 20.0 \mu$C, if particle 3 is placed at (a) $x = 40.0$ cm and (b) $x = 80.0$ cm? What should be the (c) $x$ and (d) $y$ coordinates of particle 3 if the net electrostatic force on it due to particles 1 and 2 is zero?

65 In the radioactive decay of Eq. 21-13, a $\text{C}^{28}$ nucleus transforms to $\text{Th}^{24}$ and an ejected $^4$He. (These are nuclei, not atoms, and thus electrons are not involved.) When the separation between $\text{Th}^{24}$ and $^4$He is $9.0 \times 10^{-15}$ m, what are the magnitudes of (a) the electrostatic force between them and (b) the acceleration of the $^4$He particle?

66 Two small, positively charged spheres have a combined charge of $5.0 \times 10^{-5}$ C. If each sphere is repelled from the other by an electrostatic force of 1.0 N when the spheres are 2.0 m apart, what is the charge on the sphere with the smaller charge?

67 The initial charges on the three identical metal spheres in Fig. 21-41 are the following: sphere $A$, $Q$; sphere $B$, $-Q/4$; and sphere $C$, $Q/2$, where $Q = 2.00 \times 10^{-14}$ C. Spheres $A$ and $B$ are fixed in place, with a center-to-center separation of $d = 1.20$ m, which is much larger than the spheres. Sphere $C$ is touched first to sphere $A$ and then to sphere $B$ and is then removed. What then is the magnitude of the electrostatic force between spheres $A$ and $B$?

68 An electron is in a vacuum near Earth’s surface and located at $y = 0$ on a vertical $y$ axis. At what value of $y$ should a second electron be placed such that its electrostatic force on the first electron balances the gravitational force on the first electron?

69 In Fig. 21-28, particle 1 of charge $-5.00q$ and particle 2 of charge $+2.00q$ are held at separation $L$ on an $x$ axis. If particle 3 of unknown charge $q_3$ is to be located such that the net electrostatic force on it from particles 1 and 2 is zero, what must be the (a) $x$ and (b) $y$ coordinates of particle 3? 55M

70 Two engineering students, John with a mass of 90 kg and Mary with a mass of 45 kg, are 30 m apart. Suppose each has a 0.01% imbalance in the amount of positive and negative charge, one student being positive and the other negative. Find the order of magnitude of the electrostatic force of attraction between them by replacing each student with a sphere of water having the same mass as the student.